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by

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Circular Polarizing Mirrors for High Power Lasers

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Abstract In this paper, the circular polarizing mirrors for high power lasers have been theoretically and experimentally studied, the circular polarizing mirror coated with multiple-film, which could induce 90 degrees phase retardation is prepared experimentally.

I. Introduction

Long after the high power lasers were introduced to industrial manufacturing, attention has been paid only to the effect of power, mode, speck dimension after focusing, and auxiliary gas of the laser beam on the speed and quality of industrial manufacturing, while the effect of polarization of the laser beam was rarely studied. It was generally thought that, during the manufacturing process, the input laser beams on the surface of the work piece followed the normal direction and there was no relationship between the polarization and the coupling of laser beam energy in the material. In early 1980's, it was discovered by Olsen of Denmark Institute of Technology that during the laser cutting process, the assumption that laser beam entered into the material along the normal direction was only correct in the initial reaction period. Once the cut was formed, the laser beam would skim through the surface of the work piece. Because of this reason, the reflection and absorption of laser beam by the material was strongly affected by the polarization of the laser beam.[1] For example, when laser was used in cutting or welding, the width of the cut or weld is different along different directions and the slanting of the cut or weld seam was determined by the polarization of the laser beam. Not only is polarization an important factor in laser manufacturing, it is sometimes the determining factor. After extensive study in the 1980's, the circular polarizing light was found to be the best light in operations such as cutting or welding. Circular polarizing light can not only expedite manufacturing speed, optimize manufacturing quality, it can also be used to solve many manufacturing problems not achievable with other lights.

The key element in obtaining circular polarizing light is the manufacturing of circular polarizing mirror. In this paper, the theoretical calculation and experimental manufacturing of circular polarizing mirror is studied.

II. Theoretical analysis and calculation

The best way to obtain circular polarizing light was to use polarizing element in the laser resonance cavity so that linear polarizing light can be output without loss of efficiency and power; and to use circular polarizing mirror to convert linear polarizing light to circular polarizing light with basically the same power density. The effect of circular polarizing mirror is somewhat like that of a quarter-wavelength mirror. Modern industrial manufacturing lasers are operating in the infrared range with optical power density on the order of 500W. At present, the infrared material capable of high power operation and significant double-refraction does not exist. Therefore, high power infrared laser devices could not use transmission-type quarter-wavelength mirror. As a result, multiple-film reflection devices, called circular polarizing mirror in this paper, were proposed.[2] The theoretical design and experimental manufacturing of a high power circular polarizing mirror with center wavelength 10.6μm is discussed in this paper. The design principle and manufacturing method can be used in circular polarizing mirrors with other center wavelengths.

The design requirements of a circular polarizing mirror are: 1) When the incident angle is $\theta_0 = 45°$ (θ_0 is the actual incident angle), the linear polarizing light will be decomposed into two mutually perpendicular vectors S and P waves with identical amplitude and frequency and zero phase retardation on the plane of the mirror. 2) After reflection by thin film circular polarizing mirror, the two components of the output light would have equal amplitude and maintain the same magnitude as the input light while the phase retardation of S and P waves $\pm\Delta\Phi$ was 90°. (If the left or right rotation was not distinguished than the phase retardation will be 90°.) In this manner, the output light would be basically circular polarizing light without energy loss.

Based on these requirements, the ideal laser polarizing mirror should satisfy the following two necessary conditions:

1. The reflectivity of mirror with respect to S and P waves should be basically equal and approaching 1; namely, $R_s \approx R_p \approx 1$.

2. The phase retardation with respect to S and P saves should be 90°; namely, $\Delta\Phi = \Phi_s - \Phi_p \approx 90°$. Because of manufacturing technology the actual optical multiple-film device will deviate from these ideal conditions.

The structure of circular polarizing mirror is: the substrate material was single crystal Sa and the base film material was Au or Ag; the medium film material was BaF_2 and ZnSe; the number of layers of medium film are both even numbers with high and low reflectivities alternating and the film in contact with the metallic base film was a low reflectivity material. The numbers of medium films used in this study were 10, 12 and 14. When the number of layers increased, the reflection band around $\Delta\Phi = 90°$ was wider. However, too many layers would result in a low overall reflectivity because of absorption and scattering.

The equations and symbols for theoretical calculation of circular polarizing mirror were the same as in reference [3]. The characteristic matrix of the film system is

$$\begin{pmatrix} B \\ C \end{pmatrix} = \left\{ \prod_{j=1}^{K} \begin{pmatrix} \cos\delta_j & \frac{i}{\eta_j}\sin\delta_j \\ i\eta_j\sin\delta_j & \cos\delta_j \end{pmatrix} \right\} \begin{pmatrix} 1 \\ \eta_{k+1} \end{pmatrix} \tag{1}$$

For S and P waves, the phase thickness of the film layer is

$$\delta_i = \frac{2\pi}{\lambda} N_i d_i \cos\theta_i \tag{2}$$

The angle of refraction θ_i is determined by refractivity. Conductance η_i is determined by the following equations

$$\eta_j = \begin{cases} N_j \cos\theta_j & \text{S wave} \\ N_j / \cos\theta_j & \text{P wave} \end{cases} \tag{3}$$

where N_j is the refractivity of the j-th layer material. Considering absorption and metallic base film, N_j is usually even. The composite conductance of multiple-layer medium films and metallic base layer is Y=C/B and the reflectivity of the circular polarizing mirror is

$$R = \left(\frac{\eta_0 B - C}{\eta_0 B + C}\right) \left(\frac{\eta_0 B - C}{\eta_0 B + C}\right)^* \tag{4}$$

and the reflection phase retardation is

$$\varphi = \mathrm{arctg}\left[\frac{i\eta_0 (CB^* - BC^*)}{(\eta_0^2 BB^* - CC^*)} \right) \tag{5}$$

where η_0 is the equivalent conductance of the input medium. If equations (4) and (5) were used to calculate the corresponding values for S and P waves, R_s, R_p, Φ_s, and Φ_p would be obtained and the phase retardation $\Delta\Phi = \Phi_s - \Phi_p$ would be obtained.

The purpose of circular laser polarizing mirror is to have high reflection and appropriate phase retardation. Hence, one of its characteristics is that the film thickness is not quarter-wavelength thickness and the thicknesses for each layer are different and no periodicity can be found. However, this brings great difficulty into the calculation and manufacturing of film system and makes high power laser circular polarizing mirror one of the most complicated devices of thin-film optical instrument.

The film system of circular polarizing mirror was designed on the computer with optimizing method. The optical thickness of the j-th layer was chosen as $f_j\lambda_o/4$, where $f_j \in (0,1.2)$ and was called the thickness parameter of the j-th layer, λ_o is the central wavelength (10.6μm for CO_2 laser). The target of calculation was to obtain a set of $\{f_i\}$ so that within one wavelength of λ_o the film system will have high reflectivity and 90° phase retardation. Because of this need the following evaluation function was utilized

$$F=\sum_{\lambda}\left[\ 1-\frac{1}{2}\ (R_S+R_P)+\frac{|\ \pi/2-|\Delta\varphi|\ |}{\pi/3}\ \right]^2 \qquad (6)$$

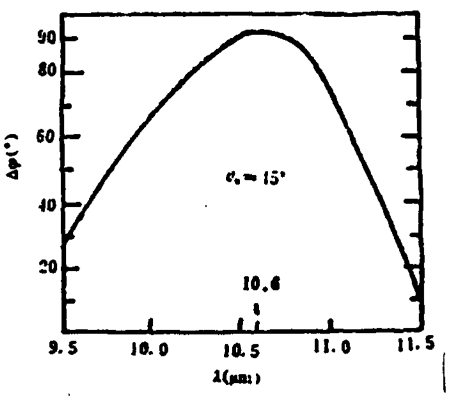
When $R_s=R_p=1$, and $\Delta\Phi=\pm\pi/2$ is established in the vicinity of λ_o, the value of F in equation (6) will become 0 and the ideal situation would be obtained. The actual computation goal was to find a minimum F for a set of $\{f_i\}$. This problem was optimized using non-linear resistance least square method. The attached table and figure show the typical f values and the relationship between the phase retardation and wavelength for a 14-layer structure for three sets of circular polarizing mirror systems with Ag as the substrate layer. Error analysis can also be carried out on the computer. The calculation showed that if the error of the thickness and refractivity were both ±1% the error of $\Delta\Phi$ was ±5%, and if the error of the thickness and refractivity were both ±2%, the error of $\Delta\Phi$ would be ±12%. When the error in

$\Delta\Phi$ exceeded ±10%. the applicability of circular polarizing mirror would deteriorate quickly. Therefore, the error in thickness and refractivity should be controlled within ±2% during manufacturing. This requirement also implied that in the experiment the film thickness should be controlled accurately and the refractivity should be measured accurately.

Table: Calculated thickness parameter f for each layer of circular laser polarizing mirror

film no.	10-layer f value	12-layer f value	14-layer f value
1	0.713	0.724	0.742
2	0.694	0.708	0.714
3	0.586	0.588	0.596
4	0.741	0.752	0.763
5	0.783	0.791	0.806
6	0.857	0.863	0.872
7	0.932	0.934	0.936
8	0.931	0.956	0.962
9	0.958	0.967	0.968
10	0.964	0.968	0.972
11		0.983	0.991
12		0.987	0.993
13			1.080
14			0.996

note: Substrate was Ag, first layer facing atmosphere.



key: 1 - Figure: Relationship between phase retardation $\Delta\Phi$ and wavelength λ for the 14th layer mirror

III. Experiment and Results

The experimental study of laser circular polarizing mirror was divided into film coating and testing. The coating was carried out by modifying DMDE-450 optical multiple-layer coating machine. Major improvements included installing a quartz-vibrating IC6000 film thickness monitor at an appropriate location within the vacuum chamber. From calculation and analysis in the previous section, it was learned that the key to the experiment was accurate measurement and control of film thickness and refractivity. Accurate control of the film thickness was achieved by combining optical thickness calibration and crystal vibration. The crystal vibration was first calibrated with high order optical thickness method and then the crystal vibration was used to monitor film thickness in real-time. In practicality, 40 layers of same material will be coated on the same control substrate using optical method and the corresponding relationship between the optical thickness and the physical thickness shown by crystal vibration would be established. After calibration of this manner, real-time monitoring of any film thickness by crystal vibration would be possible. An obvious advantage of this technique was that the monitoring wavelength between adjacent film layers could be compensated automatically and the error caused by change in molecular condensation characteristics could be avoided. After coating with the same material for 40 layers, even if the final layer showed 10% error the relative error for each single layer was only 0.25%, which is at least one order of magnitude better than other optical calibration methods. Our experiment had shown that excellent results could be obtained with this technique and automatic coating process could be greatly improved. Accurate measurement of refractivity of the film was achieved with a high precision elliptical polarizing instrument.

The properties of manufactured laser circular polarizing mirror was characterized on a high power CO_2 laser device. After the output of a CO_2 laser device was directed through a initial polarizer, the laser beams were converted to polarized light which form a 45° angle with respect to the horizontal direction. The polarized light was reflected by a coated circular polarizing mirror and the reflected light was analyzed with a analytical polarizing mirror. The values of $\Delta\Phi$ and R can be calculated through the power values at different analytical polarizing angle. Measurement of this type is a relative measurement. Analysis has shown that errors incurred by the relative measurement were within ±2° and ±1% for $\Delta\Phi$ and R, respectively. The composite test results for the circular polarizing mirror manufactured in this study were: reflectivity $R=(R_s+R_p)/2 \geq 98\%$, phase retardation $\Delta\Phi=\Phi_s-\Phi_p=90° \pm 7°$, power density $I \geq 1000 W/cm^2$. These three parameters would satisfy the requirement for circular polarizing mirrors for all industrial laser manufacturing process.

Based on the current technological level, equipment, and material supply in China, the first advanced laser circular polarizing mirror since the 80's was manufactured. This achievement should provide a stimulus to bring up the level of laser research in China.

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